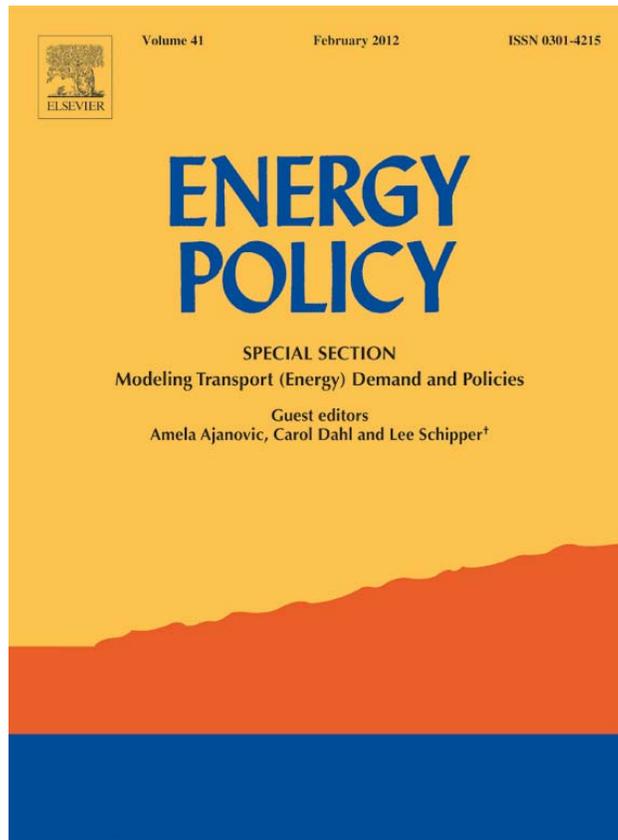


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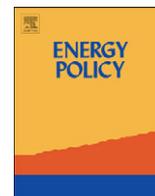
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Editorial

Modelling transport (energy) demand and policies — An introduction

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1. Introduction

Transport has been the sector with fastest growing energy consumption and CO₂ emissions world-wide. From 1971 to 2006 global transport energy use rose steadily at between 2% and 2.5% per year, closely paralleling growth in economic activity around the world. Transport accounts for about 19% of global energy use and nearly one-quarter of global energy-related CO₂ emissions. About 75% of these emissions are caused by road transport (IEA, 2009).¹ Volatile prices, energy security, investment needs to fuel an increasingly prosperous global population as well as environmental concerns have made transport fuels a popular research target for many decades with the promise of escalating interest for decades to come. Therefore, policies addressing this sector are crucial for significant CO₂ reduction.

To design energy, environmental and transportation policies that can encourage transport services with less CO₂ emissions requires a better understanding of how the demand for these services – freight and travel – evolves with the level of development, income and prices. Unfortunately many projections of fuel use in transport do not start with the basic connection between transport services and fuel.

The core objective and major contribution of this Special Issue of Energy Policy is to outline a comprehensive theoretical framework for modelling the interactions between energy and transport service demand and to bring together the most recent related work of experts organised around this framework. These papers provide the most current policy-relevant analyses for a broad spectrum of methodologies including technical component approaches and econometric investigations. This introductory editorial outlines this framework in an historical context and indicates how the papers in this issue fit into the framework.

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¹ In IEA countries (including Japan), automobiles and household SUV/light trucks account for between 75% and 85% of all energy associated with domestic travel and for 70–85% of all travel (in passenger km). For developing countries the car share of travel is much smaller, but the car share of fuel is still high because cars use so much more fuel per passenger km. Note that in most IEA countries today cars have roughly 1.5–1.6 passengers (Millard-Ball and Schipper, 2010).

2. A survey on formal frameworks and modelling approaches

The earliest papers dealing with transport fuel demand tended to consider aggregate transport fuel demand (E), most often gasoline, but sometimes diesel, total transport, or total highway transport fuel. A very few considered fuel demands for non-highway use. The bulk of these papers were econometric, with consumption related to price, income or economic activity and sometimes other variables as well.

Various models have been used in these econometric estimates. The basic single equation approach used for econometric analyses as presented, e.g. in Pindyck and Rubinfeld (1991) or Dahl and Sterner (1991a) is

$$E_t = f(P_t, Y_t, E_{t-1}) \quad (1)$$

Or in more general formulation in its common logarithm form:

$$\ln E_t = \beta_1 + \beta_2 \ln P_t + \beta_3 \ln P_{t-1} + \beta_4 Y_t + \beta_5 \ln Y_{t-1} + \beta_6 \ln E_{t-1} \quad (2)$$

where P is fuel price and Y is income.

Based on this general formulation of the model, different specific model types as listed below can be derived as in Charemza and Deadman (1997). (Note that E could be fuel demand as well as any of the components of demand such as new vehicles purchased, miles travelled, etc.)

1. Simple static model ($\beta_3 = \beta_5 = \beta_6 = 0$):

$$\ln E_t = \beta_1 + \beta_2 \ln P_t + \beta_4 \ln Y_t \quad (3)$$

2. Distributed lag model—DL ($\beta_6 = 0$):

$$\ln E_t = \beta_1 + \beta_2 \ln P_t + \beta_3 \ln P_{t-1} + \beta_4 \ln Y_t + \beta_5 \ln Y_{t-1} \quad (4)$$

3. Lagged endogenous model—LE ($\beta_3 = \beta_5 = 0$)

$$\ln E_t = \beta_1 + \beta_2 \ln P_t + \beta_4 \ln Y_t + \beta_6 \ln E_{t-1} \quad (5)$$

4. Autoregressive model—AR ($\beta_2 = \beta_3 = \beta_4 = \beta_5 = 0$)

$$\ln E_t = \beta_1 + \beta_6 \ln E_{t-1} \quad (6)$$

5. Vector autoregressive model—VAR ($\beta_2 = \beta_4 = 0$)

$$\ln E_t = \beta_1 + \beta_3 \ln P_{t-1} + \beta_5 \ln Y_{t-1} + \beta_6 \ln E_{t-1} \quad (7)$$

6. Leading indicator model ($\beta_2 = \beta_4 = \beta_6 = 0$)

$$\ln E_t = \beta_1 + \beta_3 \ln P_{t-1} + \beta_5 \ln Y_{t-1} \quad (8)$$

7. Re-parameterized as an error correction model (ECM):

$$\ln \Delta E_t = (\beta_6 - 1) \left(\ln E_{t-1} - \frac{\beta_1 - (\beta_2 + \beta_3) \ln P_{t-1} + (\beta_4 + \beta_5) \ln Y_{t-1}}{(1 - \beta_6)} \right) + \beta_2 \ln \Delta P_t + \beta_4 \ln \Delta Y_t \quad (9)$$

These basic equations can be modified in numerous ways. More lags could be added to the above stylised forms; other functional forms such as linear, polynomial, or Box Cox could also be used; other variables with or without their lags could also be added. For example, Dahl and Sterner (1991a) consider two other commonly used specifications that relate to the stock of vehicles. If one of the other variables is some measure of the stock of vehicles (V), they call the model a stock model. In its simplest form, they characterize such a model as follows.

8. Stock model:

$$\ln E_t = \beta_1 + \beta_2 \ln P_t + \beta_4 \ln Y_t + \beta_7 \ln V_t \quad (10)$$

Additionally a stock model could be formulated into any of the first 7 forms above. However, adding current vehicle stock along with lagged vehicle stock and/or a lagged endogenous variable may not make economic sense. For example, current fuel consumption is more likely to be related to the current vehicle stock. Lags in adjusting the capital stock have already been captured by inclusion of the current vehicle stock variable.

If one of the other variables is some characteristic of the vehicle stock ($Vchar$), such as average fuel efficiency, their simplest characterisation gives us model 9.

9. Stock characteristic model:

$$\ln E_t = \beta_1 + \beta_2 \ln P_t + \beta_4 \ln Y_t + \beta_8 \ln Vchar_t \quad (11)$$

The majority of econometric transport fuel demand equations have been estimated using one of the above forms. Models 2, 3, 5, and 7 specifically give short- and long-run price and income elasticities and will be referred to as dynamic models, while models 1, 8, and 9 that do not explicitly break elasticities into long and short-run will be referred to as static models. A number of surveys look at these aggregate studies for the most important transport fuel worldwide (gasoline) and come up with a summary

of short- and long-run price and income elasticities as shown in Table 1, where short-run is typically 1 year.

Three of the studies use meta-analysis and the included statistic is their mean, reference or range of elasticities. They find elasticities vary somewhat depending on model, data type and time period. For example, the inclusion of vehicles in the model lowers income elasticities and cross sectional data tends to find more elastic price and income response.

The surveys in Table 1, which span more than three decades, report a fair amount of agreement on representative price and income elasticities. The representative short-run price elasticity is most often between -0.20 and -0.30 . The representative long-run price elasticity is most often between -0.60 and -0.85 . Fewer studies consider income elasticities and the range of representative elasticities is wider. The representative short-run income elasticity is most often between 0.30 and 0.50 . The representative long-run income elasticity is most often between 0.9 and 1.4 .

None of these surveys consider studies with data beyond 2000. There is some mixed evidence that price elasticity may have fallen recently. Hughes et al. (2008) specifically consider whether there have been structural shifts in U.S. gasoline demand between the price run ups in the last half of the 1970s and the price run ups in the early part of this century. They compare estimates on monthly data for January, 1975 to January, 1980 and for March, 2001 to March, 2006 using a static model and find a monthly price elasticity of around -0.30 from 1975 to 1980 but only -0.04 from 2001 to 2006, which suggests that the short-run price elasticity is less elastic than earlier. Since Dahl (1986) found less elastic price response on monthly and quarterly data, we interpret their elasticities as very short-run. This reduction in very short-run price elasticities is not an unexpected result as vehicle durability and life spans have increased. Thus, scrappage rates have decreased, which should have slowed short term adjustment.

When Al Dossary (2008) extended stability analysis to 22 countries on annual data through 2005, he most often found structural stability over many decades. However, he did find a statistically less elastic price response for France and the U.S. since the mid to late 1980s for both the short- and long-run gasoline demand but found no evidence of a significantly less elastic price response for diesel fuel for these same 22 countries.

Looking further for a reduced elasticity in gasoline studies with data beyond 2000, we turn to the most recent posting of

Table 1
Gasoline demand elasticity surveys.

	# Studies	Study years	Psr	Plr	Ysr	Ylr
Taylor (1977)	7	70–76	($-0.10, -0.50$)	($-0.25, -1.00$)		
Bohi (1981)	11	74–78	-0.20	-0.70		Near 1
Kouris (1983) Country CSTS	7	75–83	($-0.10, -0.20$)			
Kouris (1983) US TS	7	72–83	($-0.20, -0.40$)	-0.70		
Bohi and Zimmerman (1984)	10	79–82	-0.20	Inelastic	0.40	Elastic
Dahl (1986)	69	69–84	-0.12 (m,q)		0.31 (m,q)	
Dahl and Sterner (1991a, 1991b)	~100	66–88	-0.29	-1.02	0.47	1.38
Goodwin (1992)	12	84–91	-0.26	-0.86	0.48	1.21
Dahl (1995)	14	89–93	-0.27	($-0.71, -0.84$)		
Espey (1996) U.S. (meta means)	41	69–90	-0.20	-0.60		< 1
Espey (1998) (meta means)	95	66–97	-0.16	-0.65		0.91
Graham and Glaister (2002)	113	66–00	-0.16	-0.81	0.32	0.90
Goodwin et al. (2004)	69	72–01	($-0.20, -0.30$)	($-0.60, -0.80$)	(0.35, 0.55)	(1.10, 1.30)
Brons et al. (2008) (meta means)	43	75–99	-0.25	-0.64	0.39	1.08
Studies with data since 1999, Dahl (2010)	18	02–11	-0.36	-0.81		
			-0.12	-0.45	0.21	0.87

Notes: #Studies is the number of studies in the survey. Study years indicates the range of years when the surveyed articles were published. Psr equals the reference short run price elasticity. Plr equals the reference long-run price elasticity. Ysr equals the reference short-run income elasticity. Ylr equals the reference long-run income elasticity. Elasticity numbers indicate author's reference or range of estimates. Short-run is one year unless otherwise labelled (m,q), which indicates they are monthly and quarterly, CSTS=cross section time series data, TS=time series data, < 1 means less elastic than 1, meta means are the mean elasticities from meta analysis.

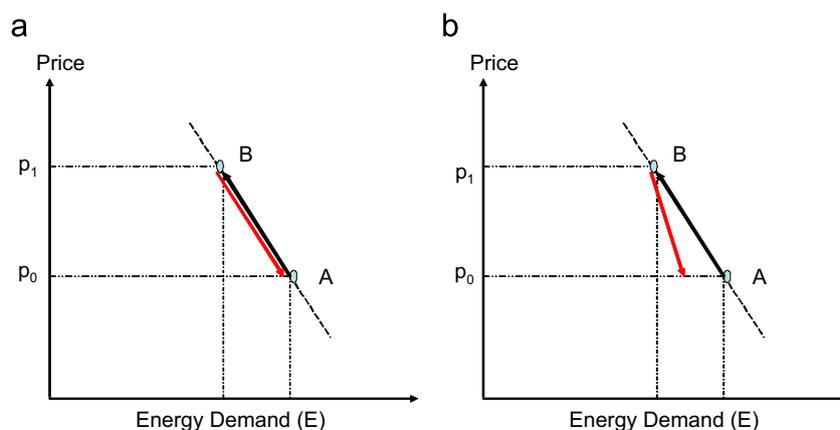


Fig. 1. (a) Symmetric model specification and (b) asymmetric model specification.

Dahl's Energy Demand Database for gasoline (DEDD-G2011.xls) (Dahl, 2011b). It includes 18 studies with 156 gasoline demand equations with data beyond 2000. The median short- and long-run price and income elasticities for these 18 studies, which are reported in Table 1, are less elastic than the most common elasticities in the earlier surveys. First and third quartiles are also less price elastic than for all 246 studies that contain econometric estimates of gasoline demand in DEDD-G2011 providing some further evidence for a reduction in demand price response. This is also not totally unexpected. As consumers have gotten richer, transport fuel expenditures have become a smaller portion of their budget, which could make them less sensitive to fuel price changes in both the short- and long-run. Increased fuel efficiency in vehicles has also tended to reduce gasoline expenditure shares for a given size vehicle.

Dahl (2011a) furthers the usefulness of these aggregate historical studies for gasoline as well as diesel demand. She finds that price and income elasticities are not constant over prices and income but that they may change in a fairly systematic way as countries develop and consumers adjust to various price levels. She uses these patterns to derive income and price elasticities for 124 countries for both gasoline and diesel fuel and challenges researchers to do further research to check the consistency of the patterns she derives from heterogeneous historical work.

Using econometrically developed price and income elasticities of aggregate transport fuel demand gives us a top-down view and can help to forecast near term increases in fuel consumption or to evaluate existing taxes. For example, Sterner (this issue) finds that OECD road fuel consumption would be around 30% higher if fuel taxes were reduced to U.S. levels. However, fuel taxes can have social effects beyond just reducing fuel consumption. Many criticise such taxes as being regressive. Sterner takes a look at the validity of such criticism using survey data for seven European countries—France, Germany, United Kingdom, Italy, Serbia, Spain and Sweden. Sterner takes as his starting point the premise that fuel prices—and thus taxes—are important for good management of climate change and other environmental problems and uses index number modelling to examine fuel tax regressivity. He finds some weak evidence for regressivity but it does not apply when lifetime income is used, nor does it apply to the poorest country in his group.

Returning to econometric work, the above nine equation types all assume that consumers respond in the same way to increasing as well as to decreasing prices. However, durability of the capital stock suggests otherwise. For example, if fuel price increases from A to B in Fig. 1a, consumers may drive less and buy smaller vehicles reducing consumption. If prices falls back down to A,

consumers are not likely to scrap their more efficient vehicles and may increase their consumption by a lesser amount than the original decrease as shown in Fig. 1b. For further discussion of this issue see Ajanovic and Haas (this issue).

There is some evidence that consumers do adjust fuel consumption asymmetrically to increasing than to decreasing prices. Dahl (2011a) mentions literature relating to gasoline and diesel consumption asymmetries while two other papers in this issue apply price asymmetry testing to specific examples on fuel consumption. Sentenac-Chemin (this issue) summarises studies that allow for asymmetry, summarises three popular decompositions, and applies the decompositions to data for the U.S. and India. Her decompositions involve three variables P_{max} , which is the historical maximum price, P_{rec} which is the cumulating series of sub-maximum price recoveries, and P_{cut} which is the cumulating series of price cuts. Thus instead of one price variable in the equation ($\beta_2 P$), all three of these variables, $\beta_{2_max} \ln P_{t_max} + \beta_{2_cut} \ln P_{t_cut} + \beta_{2_rec} \ln P_{t_rec}$, or various combinations can be included. This decomposition could be made in any of the above models with a price variable. Sentenac estimates a long-run co-integrating relationship using a stock model (model 8) and applies these decompositions to an error correction form of a stock model for gasoline (model 7) to check for short-run asymmetry of response. She finds asymmetry of response in the U.S. but not in India on data through 2005. Ajanovic and Haas (this issue) also apply asymmetry in the context of an error correction model. They find a long-run co-integrating relationships using model 1 for total passenger road transport fuel demand for six European countries on data through 2007, but do not find asymmetry of response between fuel price increases or decreases.²

Although studies are still done on aggregate demands, they are increasingly done in a wider context that breaks the aggregate demand up into components. For example, consumers do not consume gasoline directly but rather combine it with a stock of capital to produce transport services (S) Although policies that affect fuel prices may be analysed using aggregate studies, evaluating policies that more directly affect such transport services or vehicle stocks requires a better understanding of how income, price, and policy, among other variables, may affect the components of fuel decisions.

One of the earliest ways to break down transport service demand (S) from the vehicle efficiency choice, has been to estimate distance travelled (miles or metres (M)) and a demand for fuel efficiency of new cars or of the whole vehicle stock

² For other asymmetric model specifications see Gately (1992). For additional insights on asymmetries see Dargay (1992, 1993) and Walker and Wirl (1993).

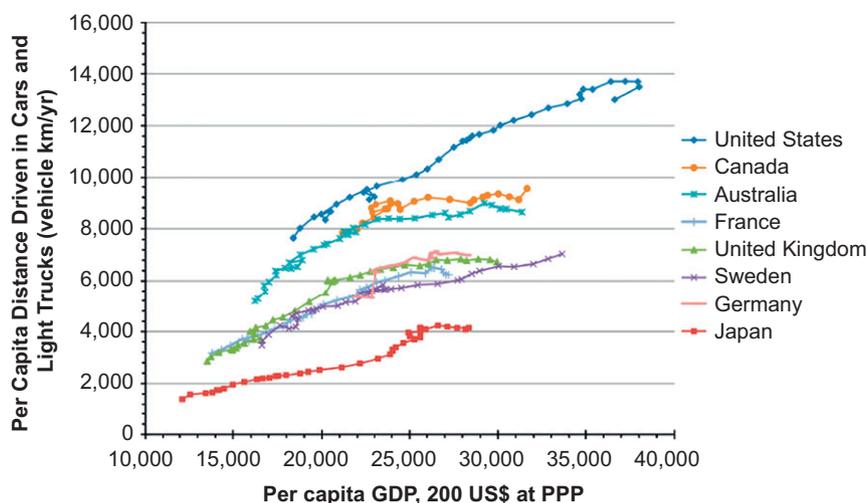


Fig. 2. Development of distance driven in cars and light trucks depending on GDP over period 1970–2007/8. Source: Millard-Ball and Schipper, 2010.

Table 2 Survey measures of central tendency for distance (M) travelled elasticities.

References	# Studies	Psr	#Psr	Plr	#Plr	Ysr	#Ysr	Ylr	#Ylr
Previous surveys									
Taylor (1977), Bohi and Zimmerman (1984)	6	-0.16	-	-0.38	-	0.42	-	0.66	-
Dahl (1986)	10	-0.32	-	-0.55	-	0.26	-	0.60	-
Oum et al. (1992)	7	-0.20	-	-0.28	-	-	-	-	-
Goodwin (1992)	11	-0.16	-	-0.33	-	-	-	-	-
Dahl (1995)	10	-0.14	-	-0.25	-	-	-	-	-
Graham and Glaister (2004)	34	-0.15	N31	-0.31	N72	-	-	-	-
Goodwin et al. (2004)	-	-0.10	N3	-0.29	N3	0.30	N7	0.73	N7
Brons et al (2008) (meta)	-	-0.20	N8	-0.53	N2	-	-	-	-
Updates from Dahl energy demand database									
Dahl (2011c) DEDD-M2011.xls	78	-0.09	N105	-0.24	N99	0.11	N94	0.31	N90
Dahl (2011c) DEDD-M2011.xls (published since 1990)	43	-0.08	N55	-0.23	N62	0.23	N39	0.58	N52
Dahl (2011c) DEDD-M2011.xls (published before 1991)	35	-0.22	N50	-0.27	N38	0.08	N55	0.18	N37
Dahl (2011c) DEDD-M2011.xls (VT=M/V)	10	-0.13	N19	-0.28	N23	0.15	N21	0.34	N24
Dahl (2011c) DEDD-M2011.xls (not/V)	68	-0.09	N86	-0.22	N76	0.11	N73	0.31	N66

Notes: See notes under Table 1 for some definitions. Additional definitions include the following. M indicates total miles, miles per some measure of population, or miles per vehicle. N# indicates the number of estimates in an elasticity category. - Indicates data are not available. VT=M/V indicates studies where the dependent variable was distance travelled divided by some measure of vehicle stock. (M/V) is the coding used in DEDD_M2011. not/V are all studies that are not distance per vehicle. Meta indicates the summary statistic is from a meta-analysis.

measured as distance per quantity of fuel (e.g., miles or metres per quantity of fuel), which we can abbreviate as (Mpq). Then fuel or energy consumed is

$$E = \frac{M}{Mpq} \tag{12}$$

Each of these components is likely to be influenced by a variety of economic factors. For example, the relationship for passenger transport demand and income is visualised in Fig. 2. We can see that in all countries the demand for the service “vehicle km driven” moves almost linearly with GDP. However, in some countries a slight decline in passenger car use in the past few years can be noticed, e.g., in Australia and some European countries.

A number of previous studies have surveyed price and sometimes income elasticities for the component M. Representative measures of central tendency for these elasticities in the short- and long-run are compiled in Table 2. All representative short-run price elasticities lay between -0.10 and -0.32. Representative long-run price elasticities vary a bit more widely between -0.25 and -0.55. The long-run price response is between 1.7 and

1.9 times larger than the short-run response. All representative short-run income elasticities lay between 0.26 and 0.42. Representative long-run income elasticities vary more widely between 0.6 and 0.73. The long-run income response is between 1.5 and 2.5 times larger than the short-run response. For more comprehensive summary statistics, we turn to Dahl’s online Energy Demand Database for studies that estimate demand for travel (DEDD-M2011) (Dahl, 2011c). It contains 74 studies published between 1969 and 2010 with 435 estimated equations relating to passenger car transport demand in over 20 countries. The median elasticities in DEDD-M2011, which are shown in Table 2 (lower part), show demand price and income responsiveness to be at the less elastic edge or below earlier summary statistics with median short/long-run price and income elasticities (-0.09/-0.240), (0.11/0.30).

If we consider only the studies in M2011 published since 1990, the median price elasticities are similar but the median income elasticities approximately double and become nearer to those on earlier surveys. If we consider only studies published before 1991, the median price elasticities are similar to the earlier surveys but income elasticities are surprisingly low. These medians suggest

that price elasticities may have fallen and income elasticities may have risen in the last two decades. These hypotheses could be checked by meta or other statistical analysis on these existing studies as well as designing entirely new studies to address them. We did not find much difference in medians for studies on travel demand that included a stock of vehicle variable than from those that did.

A number of studies in this issue consider demand for distance travelled. Ajanovic and Haas estimate a demand for distance travelled on 6 European countries for passenger car transport. They find long-run co-integrating relationships for all six in the context of an error correction model on data through 2007 models 1 and 7. Distance travelled is also often a component in larger transportation models. Anable et al. (this issue) and Brand et al. (this issue) both use the UK transport carbon model (UKTCM). This bottom-up model of transport carbon emissions contains a transport demand module. Within this module, econometric travel demand equations are functions of GDP, number of households and vehicle capital and operating costs for a variety of service demands including passenger travel (passenger km) by car, bus, rail and air as well as freight demand (tonne km) by van, truck, rail, water, and air.

In the above surveys of fuel demand, price was found to be a prominent driver of fuel consumption. One likely way price will influence the fuel decision is through the amount of fuel a vehicle uses per unit of travel. This fuel use is typically measured in two ways. One way is through vehicle fuel efficiency, distance per fuel

use (Mpq) as designated above, or its inverse called fuel intensity (FI), which is fuel use per distance travelled with $FI=1/Mpq$ (e.g., l/100 km). The relationship between fuel intensity and fuel price can be seen in Fig. 3 for 1985 and 2007. For example, the United States has had the highest fuel intensity and lowest fuel prices, whereas Italy has had the highest fuel prices with resulting low fuel intensities.

Such fuel intensities (FI) or their inverse (Mpq) may also be influenced by income. Econometric equations, such as models 1–9, can be used to measure the price and income effect. We have found four studies that survey such estimates for Mpq for short- and long-run price and sometimes income elasticities as shown in Table 3. The summary statistics suggest that as fuel price increases 1%, vehicle efficiency increases from 0% to 0.17% in the short-run and from 0.14% to 0.31% in the long-run. Two earlier surveys Bohi and Zimmerman (1984) and Dahl (1986) concluded that when income increases 1%, people buy larger and less fuel efficient cars and the vehicle fleet efficiency decreased by 0.07% in the short-run and around 0.20% in the long-run. More recently, Dahl (1995) found ambiguity in the income elasticity estimates and came to no conclusion about a summary statistic. Earlier studies suggested a negative income relationship, while studies nearer to 1995 often found a positive relationship.

Dahl's Online Energy Demand Database for Mpq (DEDD-Mpq2011) includes 31 studies with 125 equations for Mpq of the passenger fleet published between 1974 and 2010 (Dahl, 2011d). About three quarters of the estimates are for the U.S. and

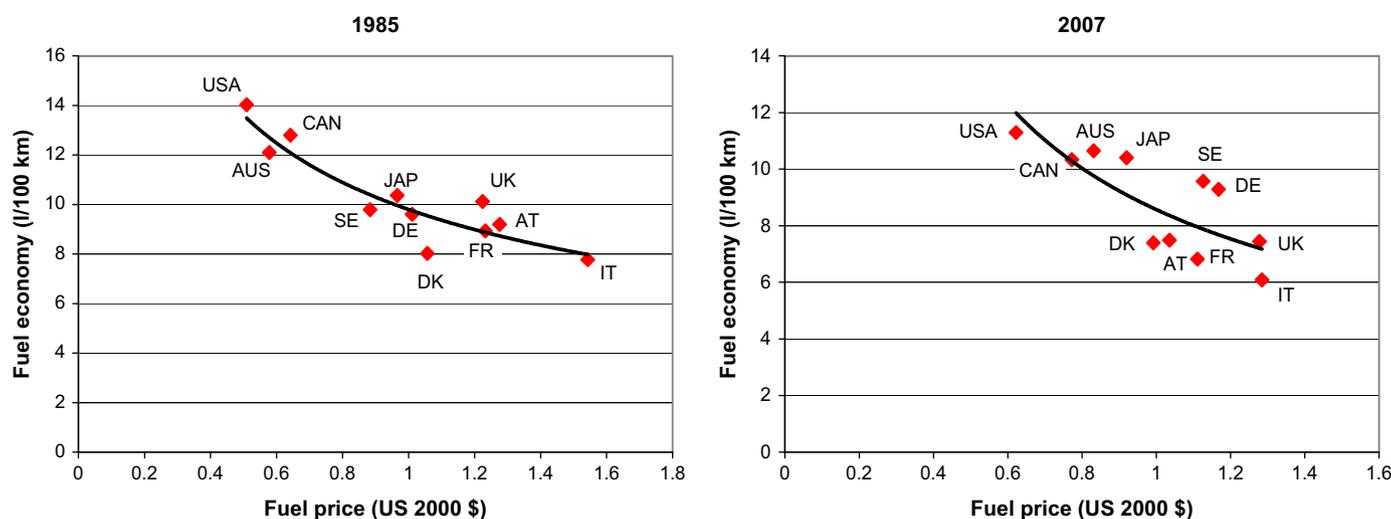


Fig. 3. Car fuel intensity versus average fuel price, 1985 and 2007.

Table 3

Survey measures of central tendency for vehicle efficiency (Mpq =distance/quantity of fuel=1/ FI) elasticities.

References (Mpq)	# Studies	Psr	#Psr	Plr	#Plr	Ysr	#Ysr	Ylr	#Ylr
Previous surveys									
Bohi and Zimmerman (1984)	3	0.13	N5	0.30	N3	-0.07	N3	-0.18	N3
Dahl (1986)	8	0.17	-	0.57	-	-0.07	-	-0.21	-
Dahl (1995)	8	0.00	-	0.14	-	-	-	-	-
Brons et al. (2008) (meta)	-	0.14	N11	0.31	N4	-	-	-	-
Updates from Dahl energy demand database									
Dahl (2011d) DEDD-Mpq2011.xls	32	0.03	N46	0.23	N53	-0.03	N15	-0.06	N24
Dahl (2011d) DEDD-Mpq2011.xls (published since 1990)	15	0.00	N20	0.14	N23	-0.03	N14	-0.15	N18
Dahl (2011d) DEDD-Mpq2011.xls (published before 1991)	14	0.13	N26	0.63	N30	0.08	N1	-0.03	N6

Notes: See notes under Tables 1 and 2 for some definitions. The elasticity of fuel intensity (FI) with respect to any variable X equals minus the elasticity of Mpq with respect to X : $\partial \log(FI) / \partial \log(X) = \partial \log(1/Mpq) / \partial \log(X) = \partial \log(1) / \partial \log(X) - \partial \log(Mpq) / \partial \log(X) = -\partial \log(Mpq) / \partial \log(X)$.

the remainder are on 8 other countries or are estimations on cross sections or cross section time series of up to 43 countries. Median elasticities from these studies are shown in Table 3. Both short- and long-run median price elasticities are positive and within the range of the earlier studies. Looking more closely at the distribution of study elasticities, studies which omit an income variable find long-run price elasticities around 4 times as large as those that include an income variable. Where income is included, it is significant in the majority of cases (taken as $|t| > 1.645$). If we stratify the studies into those before 1991 and those since 1990, the medians suggest a more elastic price response in the earlier period as was the case for fuel and travel demand. However, this conclusion is not supported by studies with no included income variable. Fewer studies include income elasticities and income elasticities are more ambiguous. The long- and short-run medians are negative and less elastic than for earlier surveys except for the one study published before 1991. They suggest that as income increases consumers buy slightly less efficient autos. Thus, consumers may upgrade to larger automobiles with more fuel using accessories. However, the majority of income elasticities in the 72 static models from 20 different studies suggest income elasticities may be small and positive. Thus, as in Dahl (1995) we can come to no conclusion about the size or sign of the vehicle efficiency with respect to income. We suspect both effects are occurring with higher incomes leading to a newer more fuel efficient vehicle stock which is offset by purchases of larger, heavier, roomier, more powerful vehicles with more accessories.

A number of issues may have contributed to this ambiguity for income elasticities. Data quality for miles travelled and fleet efficiency are suspected to be of more dubious quality than for fuel consumption. This problem and how data sources and calculations are often misused to hide data problems has been outlined in Schipper et al. (1993a). Paucity of data have also restricted such studies to wealthier countries, which have often had policies relating to fuel consumption that may have changed people's behaviour over time. Of the 660 equations in DEDD-M2011 and DEDD-Mpq2011 over 80% are estimated for countries with a median per capita income³ greater than \$15,000 per capita in real 2010 USD. Two-thirds of the studies are on the U.S., which has had fuel efficiency standards in place since 1978.

Nine countries have such fuel standards and a number of other countries are considering implementing them (An et al., 2011). An important policy issue relating to such fuel standards is the effect they might have on transport service demand. Since raising fuel efficiency (*Mpq*) or lowering fuel intensity (*FI*) lowers the fuel cost of driving a kilometre, it may increase the number of kilometres driven. Thus, some fuel savings from the efficiency gains may be offset by the extra driving. Service demand does not include only distance travelled but is rather a complex mix of distance, power and weight of cars and comfort. Some of the fuel savings may also be used for an increase in some of these other features that may require more fuel. This offset is called the rebound effect. To more formally develop the rebound effect, recall that energy consumption can be written as service demand (*S*) for transport times fuel intensity (*FI*).

These services are in general provided by combining different inputs of energy and technology, assuming that human and physical capital is largely accumulated in the technical efficiency of the technologies used – conversion as well as infrastructure – see Haas et al. (2008) and Walker and Wirl (1993)

$$E = S \cdot FI \quad (13)$$

Note that this Eq. (13) is equivalent to Eq. (12), where service is distance travelled (*M*).

The above mentioned rebound effect is one of the most critically discussed issues with respect to the implementation of standards for fuel intensity or corresponding CO₂. Using Eq. (13), as described in Greene (1997), the rebound effect can be derived by means of identifying the elasticity of energy consumption with respect to a change in fuel intensity $\gamma_{E,FI}$ as follows:

$$dE = \frac{\partial E}{\partial S} dS + \frac{\partial E}{\partial FI} dFI = FI dS + S dFI \quad (14)$$

The change with respect to FI is (see also Ajanovic and Haas (this issue)):

$$\frac{dE}{dFI} = FI \frac{dS}{dFI} + S \frac{dFI}{dFI} = FI \frac{dS}{dFI} + S \quad (15)$$

Next, we analyse what is the relation between changes in *FI* and the service price elasticities. Using this relationship and the definition for the elasticities of energy consumption with respect to a change in fuel intensity we obtain:

$$\gamma_{E,FI} = \frac{dE/E}{dFI/FI} = \frac{dE}{dFI} \frac{FI}{E} = \left(FI \frac{dS}{dFI} + S \right) \frac{FI}{E} = \frac{FI}{E} FI \frac{dS}{dFI} + \frac{FI}{E} S \quad (16)$$

Substituting *E* with *S***FI* gives

$$\gamma_{E,FI} = \frac{FI}{SFI} FI \frac{dS}{dFI} + \frac{FI}{SFI} S = \frac{FI}{S} \frac{dS}{dFI} + 1 \quad (17)$$

Considering that service demand also depends on service price *P_S*

$$P_S = P_E FI \quad (18)$$

and

$$dP_S = P_E dFI \quad (19)$$

where *P_E* is energy price, we finally obtain

$$\gamma_{E,FI} = \frac{dE}{dFI} \frac{FI}{E} = \frac{FI dS}{S dFI} \frac{P_E}{P_E} + 1 = \frac{P_S dS}{S dP_S} + 1 = \alpha_{S,P_S} + 1 \quad (20)$$

From the last equation it can be seen that the elasticity of energy consumption with respect to a change in fuel intensity ($\gamma_{E,FI}$) is one plus the elasticity of energy service with respect to service price (α_{S,P_S}) (see also Walker and Wirl, 1993).

If the fuel intensity is constant ($dFI=0$) in the short-term, we can show that the elasticity of energy consumption with respect to a change in fuel price (*P_E*) is equal to the elasticity of energy service with respect to service price (*P_S*) as follows. From Eq. (15), if we obtain

$$dE = FI dS \quad (21)$$

and related to a change in fuel price *P_E*

$$\frac{dE}{dP_E} = \frac{FI dS}{dP_E} = \frac{FI dS P_S}{dP_E P_S} = \frac{FI dS P_E FI}{dP_E P_S} = \frac{E}{S} \frac{dS}{dP_S} \frac{P_S}{P_E} \quad (22)$$

can be rewritten

$$\frac{dE/E}{dP_E/P_E} = \frac{dS/S}{dP_S/P_S} \quad (23)$$

So, if *FI* remains constant

$$\alpha_{E,P_E} = \alpha_{S,P_S} \quad (24)$$

The above derivations show the relation between *E* and its components *S* and *FI*. This is especially important to assess the impact of policies. Taxes have a direct impact on *S* and in the long-run also on *FI*. Standards directly affect *FI* and indirectly *S*.

With the relationships derived above, it is possible to identify rebound effects with respect to distances driven and size of cars and to design policy portfolios in a way where taxes may

³ The median income is taken to be the average of the per capita income for the first and last year of the study's sample.

compensate for the rebound due to technical standards for FI or CO_2 . The rebound effect is analysed in four papers of this special issue. [Greene \(this issue\)](#) uses U.S. national time series data on vehicle travel by passenger cars and light trucks, covering the period 1966–2007 to test for the existence, size and stability of the rebound effect for motor vehicle fuel efficiency (using Eqs. (16) and (17)). His analysis shows a statistically significant effect of gasoline price on fuel economy but does not support the existence of a direct impact of fuel efficiency. Additional tests indicate that fuel price effects have not been constant over time, although the hypothesis of symmetry with respect to price increases and decreases is not rejected. [Matiaske et al. \(this issue\)](#) addresses the empirical question of the extent to which higher fuel efficiency of cars affects additional travel. Their analysis is based on Eqs. (14) and (15) with data taken from the German Socio-Economic Panel (SOEP). They estimate an unbalanced two-wave random effects panel model. Their results suggest that car efficiency has a negative effect on the kilometres driven for cars with relatively high fuel consumption and they find a positive diesel effect on the distance driven. Some preference variables such as certain attitudes towards the environment amplify the non-linear rebound effect. [Goerlich and Wirl \(this issue\)](#) focus on the interdependencies between technical efficiencies and energy demand. Their paper uses technical efficiencies as one crucial determinant of energy demand in order to integrate at least two issues that are usually investigated separately from each other: the rebound effect resulting from improved technical efficiencies and the asymmetry of energy demand. They use Austrian data to support their argument that consumers do not apply high implicit rates for discounting the future benefit from efficient cars in the purchasing decision of diesel versus gasoline powered cars.

[Ajanovic and Haas \(this issue\)](#) also address the rebound controversies. They analyse the impact of changes in fuel prices and fuel intensity (i.e., litres of fuel used per 100 km) on overall fuel (gasoline plus diesel) consumption and on the demand for vehicle km driven in car passenger transport. Their goal is to derive effective policy portfolios consisting of fuel taxes and technical standards such as fuel intensity mandates or specific CO_2 emission limits. To extract these impacts, they apply co-integration analyses to six European countries and their aggregate over the period 1970–2007. They also investigate how changes in fuel prices and fuel intensity interact, by analysing the rebound effect due to lower fuel intensity and the switch to diesel using Eqs. (14) and (15). The major conclusion of their analysis for policy makers is that technical standards as the only policy instrument will have limited success. Thus, they recommend increased fuel taxes along with fuel intensity standards so that the taxes compensate for the rebound due to the standards.

Fuel efficiency standards can have important implications for FI and for service demand, while the efficiency of the fuel used also has a bearing on FI . Numerous countries have had policies relating to fuel use. There are a number of advantages to diesel fuel compared to gasoline, such as the higher thermal efficiency, higher energy density, and lower diesel fuel taxes along with advantages of diesel engines such as greater reliability, greater durability, lower maintenance costs and less CO_2 emissions (diesel vehicles burn on average 30% less fuel and produce 25% less CO_2 emissions than petrol vehicles ([ACEA, 2004](#))). These advantages have caused the remarkable shift to diesel passenger cars in Europe shown in [Fig. 4](#).

Three papers in this issue ([Ajanovic and Haas](#), [Matiaske et al.](#), [Görlich and Wirl](#)) deal with the effects of a switch to diesel fuel, focusing on the rebound effect. All three papers find clear evidence for a rebound with respect to vehicle kilometres driven when switching to diesel. In addition [Görlich and Wirl](#) also document the rebound due to a switch to larger cars when using diesel.

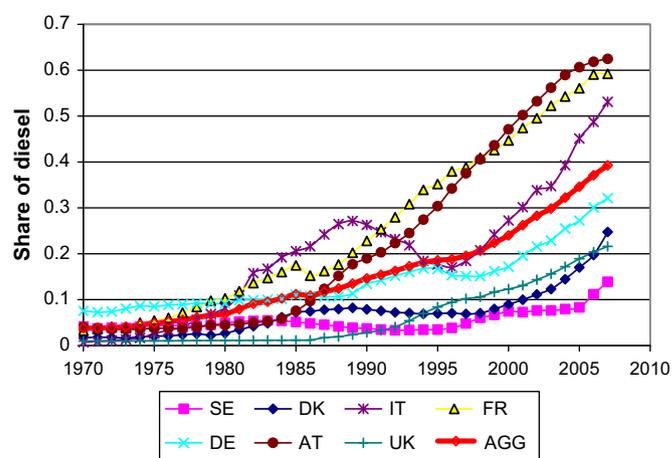


Fig. 4. Increase in the share of stock of diesel cars in the countries investigated and the aggregate of the countries.

Although the type of fuel used contributes to FI , the vehicle stock is even more important. Up to now we have only considered how the vehicle stock in aggregate in model 8, and how characteristics of the vehicle stock in model 9 directly influence fuel use. We have also considered how economic variables specifically influence the characteristics of Mpq and FI and service demands. We can further break service demand (S) into two components: Long-term service demand S_{LT} (vehicle stocks and their characteristics (V)) and short-term service demand S_{ST} (miles or km driven per vehicle (VT)). So, for empirical analyses the structure is

$$S_t = S_{LTt} S_{STt} = V_t VT_t \quad (25)$$

Inserting Eq. (25) into (13) yields:

$$E_t = V_t VT_t FI_t \quad (26)$$

[Cuenot et al. \(this issue\)](#) use Eq. (26) as a basic building block of the IEA global mobility model (MoMo) with 25 world regions and a variety of passenger and freight modes for 1975–2050. They further break vehicle traffic into passenger and freight travel using load factors, and simulate the effect of changing transport mode and trip type (urban versus rural on energy use and emissions).

There are various ways to get the inputs to the above equation as well as other breakdowns of energy demand. For large long term models such as the IEA model, described in [Cuenot et al.](#) the inputs are often developed through policy simulations and scenarios. Such scenarios can be used to represent lifestyle and socio-cultural changes as in [Anable et al. \(this issue\)](#).

Alternatively, all three input variables in Eq. (26) can be estimated econometrically or developed from scenarios. Econometric estimates of FI (usually estimated as its inverse $1/FI = Mpq$) have been discussed above. Similarly VT can be estimated econometrically. There are 10 econometric studies with 30 estimated equations for VT in DEDD-M2011. The earliest was published in 1977 and the latest in 2008. Five of the studies are on the U.S., one is on Mexico, one on 4 Scandinavian countries and the other three are on cross sections or cross section time series of up to 42 countries. Medians for these studies are included above in [Table 2](#). The median short- and long-run price and income elasticities for VT at $(-0.13/-0.28)$ and $(0.15/0.34)$ are not very different from those that normalise travel demand by some measure other than vehicle stock.

Vehicle ownership can also be arrived at in a variety of ways. [Graham and Glaister \(2004\)](#) survey econometric work on the demand for car ownership. They find the mean short/long-run price and income elasticities to be $(-0.20/-0.90)$ and $(0.28/0.74)$, respectively.

Per capita ownership has been estimated as a function of per capita GDP in Dargay and Gately (1999) and Meyer et al. (this issue) using the following Gompertz-function:

$$V_t = V^* e^{\gamma e^{\delta(GDP_t)}} \quad (27)$$

where V_t is vehicles per 1000 people in year t , V^* is estimated vehicle ownership saturation level in vehicles per 1000 people, GDP_t is per capita income in year t , and γ and δ are estimated parameters that show consumer behaviour as population increases.

The income elasticity (η_t) for V_t is

$$\eta_t = \gamma \delta (GDP_t) e^{\delta(GDP_t)} \quad (28)$$

This income elasticity is not constant, but rather increases and then declines as income increases and the region approaches saturation. Cuenot et al. (this issue) use such functions by region to project vehicle ownership but base their modal shares on trends. More formal popular alternatives to choose transportation, technology, or fuel modes are discrete choice models (Train, 2009). For example, a logistics model is used in the UK Transport Carbon Model (UKTCM) to choose vehicle types for both freight and passenger vehicles in both Brand et al. (this issue) and Anable et al. (this issue).

Meyer et al. in this issue apply three approaches to forecast the light duty vehicle fleet to 2050 for 11 world regions. In one approach, they estimate a Gompertz function with per capita car stock a function of per capita income as above with constant preferences across their 11 world regions and years which vary by region but all lie between 1960 and 2006. In another similar approach to the Gompertz, they assume a saturation level of 1 vehicle per capita and econometrically regress the logit transformation of per capita car stock on a constant and per capita income on their 11 regions. In a third, they develop a function from micro-theory for a Stone–Geary utility function with the vehicle stock and all other goods. They assume saturation with a constant budget share for travel for industrial countries with emerging markets approaching a constant saturation of 11% over a 20-year period. All three models assume that consumer preferences for vehicle purchases are largely driven by per capita income with similar functions across regions. For their models with saturation built in, their Gompertz model yields 50% higher car stocks in 2050 than their panel logistic estimates.

Any vehicle stock can be modelled in more detail with technical change across time. In the simplest case, new cars (V_{new}) are separated from existing cars (V) as in the following equation:

$$V_t = V_{t-1} - V_{scr,t-1} + V_{new,t} \quad (29)$$

where V_{scr} is the number of scrapped vehicles.

Such equations can be disaggregated in various ways with vehicle stock, new cars and scrappage computed by technology as described in detail by Christidis et al. (2003), Zachariadis (2005) as well as in Anable et al. (this issue), Brand et al. (this issue) and Cuenot et al. (this issue). The new and existing stock of vehicles along with scrappage can be modelled econometrically, can be created from policy scenarios, or can even be chosen from an optimisation model (e.g. given fuel prices and vehicle costs, the model could pick the vehicle that minimises the cost of transportation). Fuel use at any time t can then be created from the N vintages as follows:

$$E_t = \sum_{i=1}^N V_{it} VT_{it} FI_{it} \quad (30)$$

where V_{it} is the existing vehicles of vintage i at time t , VT_{it} is the travel per vehicle of vintage i at time t , and FI_{it} is the fuel intensity of vehicles of vintage i at time t .

Eq. (30) has important policy applications. Currently many transport policies are related to reducing CO₂ emissions. For example, the fleet average to be achieved in the period 2012–

2015 by all new passenger cars registered in the European Union is 130 g CO₂/km. Due to a phase-in mechanism, the 130 g CO₂/km target only enters into full force in 2015⁴ (EC, 2010). Even emerging markets are including transport policy in their Climate Action plans. India includes transport pricing reform and regulatory standards, while Brazil and Mexico propose increasing the share of rail transport (WRI, 2009).

We can easily compute CO₂ emissions from energy consumption in Eq. (26) as follows:

$$CO_{2t} = E_t f_{CO_{2t}} = V_t VT_t FI_t f_{CO_{2t}} \quad (31)$$

where $f_{CO_{2t}}$ is coefficient of CO₂ emissions per energy unit consumed at time t .

We can break CO₂ emissions into components by applying the total differential to Eq. (31)

$$dCO_{2t} = \frac{\partial CO_{2t}}{\partial V_t} dV_t + \frac{\partial CO_{2t}}{\partial VT_t} dVT_t + \frac{\partial CO_{2t}}{\partial FI_t} dFI_t + \frac{\partial CO_{2t}}{\partial f_{CO_{2t}}} df_{CO_{2t}} \quad (32)$$

By applying Eq. (32) to either historical data or policy simulations, we can determine how much CO₂ comes from increasing vehicles (V), how much comes from increasing travel per vehicle (VT), how much comes from changes in the fuel intensity (FI) and how much comes from changing the fuel mix (f_{CO_2}).⁵ This approach could be further broken down by vintages or technologies. Anable et al. (this issue), Brand et al. (this issue), Cuenot et al. and Meyer et al. in this issue all include some estimation of CO₂ emissions in varying levels of detail in their modelling outputs. Indeed all use the building blocks considered in our paper but they cover a range of transport, energy, and environment issues. For more on such hybrid models, we refer you to the papers themselves or to Evans and Hunt (2009), which also includes a wide variety of other models.

It is quite easy to modify Eq. (32) to break down the effect of other variables. For example, if we wanted to consider population's (Pop) effect, we could write

$$CO_{2t} = Pop_t \frac{V_t}{Pop_t} VT_t FI_t f_{CO_{2t}} \quad (33)$$

Although our discussion and breakdowns, so far, have tended to focus on passenger transport, everything we have done could as easily be related to freight. S could be tonne miles, V could be trucks, FI could be energy use per tonne mile. Econometric models 1–9 could also be used to model freight services, but we have not found very much econometric work relating to freight services. Studies on diesel fuel demand, which historically has tended to be largely used for freight and bus transport, are a bit more abundant. DEDD-D2010.xls (Dahl, 2010) contains 61 studies with 324 estimates on more than 50 countries that estimate the demand for diesel fuel. There is a fair amount of variation across the studies. The median short- and long-run price and income elasticities are (–0.10/–0.31) and (0.39/1.36), respectively, suggesting that the demand for diesel fuel is likely to be less price and more income elastic than for gasoline. Graham and Glaister (2004) also note the paucity of estimates for freight transport service demand (typically measured as tonne miles) but are able to survey price elasticities from 16 available studies published from 1979 to 1998. They find two-thirds of the price elasticities estimates

⁴ The target of 130 g CO₂/km is phased-in from 2012 to 2015 where only 65% of the new fleet should comply with the target in 2012, 75% in 2013, 80% in 2014, and 100% as of 2015.

⁵ This is a vehicle specific example of the well-known ASIF formula for kg CO₂ emissions for a particular fuel (see Schipper et al., 2000): $CO_2 = AS_{ST} FI f_{CO_2}$ where A is the activity (e.g., population); S_{ST} is the service demand per person; f_{CO_2} is the fuel-specific CO₂ emissions (e.g., kg CO₂/l fuel).

lie between -0.5 and -1.3 , but find too much methodological variation across the studies to come up with any reference elasticities.

The three large long term modelling efforts in this issue Anable et al., Brand et al., and Cuenot et al. all include freight transport modelling in a parallel fashion to passenger transport modelling and include demands for tonne miles, stocks, purchases and scrappage of freight moving vehicles by technologies and vintage.

For freight transport, over-all economic activity such as GDP or industrial production as well as the total amount of goods shipped has an impact. The basic approach of Eq. (13) can be extended into a GDP-based index approach as follows:

$$E = GDP \frac{M_V}{GDP} \frac{S}{M_V} FI \quad (34)$$

where GDP is gross domestic product, M_V is value of manufactured goods, and S is distance driven (vkm).

Sorrell et al. (this issue) use this approach to break down freight energy use in the U.K. even further into ten factors by commodity as follows:

$$E_{ckt} = GDP_t \frac{MfgD_t}{GDP_t} \frac{MfgD_{ct}}{MfgD_t} \frac{MfgT_{ct}}{MfgD_{ct}} \frac{TonT_{ct}}{MfgT_{ct}} \frac{TonHv_{ct}}{TonT_{ct}} \frac{TonHv_{cct}}{TonHv_{ct}} \times \frac{TonM_{ckt}}{TonHv_{ct}} \frac{VML_{ckt}}{TonM_{ckt}} \frac{VMT_{ckt}}{VMT_{ckt}} \frac{E_{ckt}}{VMT_{ckt}} \quad (35)$$

where c is the commodity; E_{ckt} is the fuel consumption during time t by vehicle type k to move commodity c ; GDP_t is the gross domestic product during time t ; k is the vehicle weight and type categories; $MfgD_t$ is the value of domestically manufactured goods during time t ; $MfgD_{ct}$ is the value of domestically produced manufactured good c during time t ; $MfgT_{ct}$ is the value of total supply of manufactured goods c during time t ; $TonT_{ct}$ is the total tonnes of manufactured goods c transported by all modes; $TonHv_{ct}$ is the total tonnes of manufactured goods c transported by heavy goods vehicles; $TonHv_{cct}$ is the total tonnes of manufactured goods c transported by vehicle type k ; $TonM_{ckt}$ is the total tonne kilometres of manufactured goods c transported by heavy goods vehicle type k ; VML_{ckt} is the vehicle kilometres driven by heavy goods vehicle loaded; VMT_{ckt} is the total vehicle kilometres driven by heavy goods vehicles.

They conduct their breakdown for 1989–2004 when road freight fuel consumption grew considerably slower and appeared to have been decoupled from GDP growth. From this index approach, they found the declining value of manufactured goods relative to GDP a major contributing factor to the decoupling with smaller payload weight, less empty running and lower fuel use per vehicle kilometre also making a contribution. Thus the shift towards the service sector in the U.K. more than offset the small increase in energy intensity per £ of manufactured goods.

3. Future challenges for energy transport fuel modelling

One of the major goals of this special issue is to provide policy makers with a sound foundation for future energy scenarios and energy policy evaluation. All of the modelling efforts and methodologies above, even if not designed or applied to evaluate specific policies, have policy implications. Some policies are directed specifically at transport fuels or fuel use as in this issue. Other policies are more broadly aimed at transportation or even land use that have strong implications on transport fuel use. Studying transport use in this broader context is important since there are far more components contributing to transport cost than just fuel. Vehicle costs (ownership, insurance), variable costs like parking and tolls, as well as the value of time in travel all may play a role in transport decisions. Moreover, transport is associated with significant externalities, particularly air pollution, accidents, and congestion. Changes in the basic costs of transportation, as well as Pigouvian taxation aimed at the major externalities, could have greater effects on transport demand than changes in fuel prices. Regarding the many possibilities on how different pricing schemes and fiscal policies could impact these various aspects of transport demand, VTPI (2010) provides the very nice overview shown in Table 4. The effect of all such policies on fuel use are still open areas for study but require micro-level data and analysis of behavioural trends.

Demand for transport fuel is derived from the demand for transport services (in person or tonne-kilometres) in turn provided by feet, pedals, animal power, and for much of the world, motor vehicles and rail engines on land, ships on water and aircraft. While there are reasonably reliable data on fuel consumed for “road transport” (trucks, cars, buses, two- and three-wheeled vehicles), “rail”, “air” and “water”, there are few primary data published dividing these by passenger and freight modes except in a dozen IEA countries. And there are almost no regularly published data on vehicle kilometres, passenger kilometres or tonne-kilometres by mode outside of IEA countries. Since automobiles only provide a small share of passenger transport in the developing world, this means that most travel is outside our modelling ability. Moreover, the demand for mobility (in passenger-km) is focused in urban regions in the developing world, where congestion often slows traffic to a crawl (Schipper and Fabian, 2009a). Unless better statistics on the most important growing regions of the world are forthcoming our ability to model energy use as a derived demand from transport will worsen.

A narrow specification of transport energy demand in terms of fuel prices and incomes (the traditional approach) may be appropriate when the dominant form of transport is automobiles and when freight demand is overlooked. However, the appearance of millions of electric bicycles in China (IEA, 2009), and the potential for mini cars in India (Schipper et al., 2009b) and more

Table 4
Impacts of different types of pricing on different components of transport demand.
Source: Adapted from VTPI (2010).

Type of impacts	Vehicle fees	Fuel price	Fixed toll	Congestion pricing	Parking fee	Transit fares
Vehicle ownership: Consumers change the number of vehicles they own.	X	X			X	X
Vehicle type: Motorist chooses different vehicle (more fuel efficient, alternative fuel, etc.).	X	X				
Route change: Traveller shifts travel route.			X	X	X	
Time change: Motorist shifts trip to off-peak periods.				X	X	
Mode shift: Traveller shifts to another mode.		X	X	X	X	X
Destination change: Motorist shifts trip to alternative destination.		X	X	X	X	
Trip generation: People take fewer total trips (including consolidating trips).		X	X	X	X	X
Land use changes: Changes in location decisions, such as where to live and work.			X		X	X

generally two wheelers in much of the developing world provides strong caution against equating ownership of private cars to fuel demand. Moreover, it is widely believed that most future growth in car ownership will be in Asia (IEA, 2009). But profound space constraints there and increasing levels of congestion (in Latin America as well) suggest that new cars may become increasingly smaller and driving distances will fall because of low-speeds and congestion (Ng et al., 2010; Schipper, 2008; Schipper et al., 2009a, 2009b). How this “crunch” will affect future fuel use deserves considerable study. As Ng et al. (2010) point out, space constraints, slower speeds and the stop-and go traffic of very congested urban regions may favour small electric vehicles that do not waste energy idling.

So a more critical and complete approach is needed. It could include both direct variable costs (parking, tolls, etc.), unpaid direct costs (time), and fixed costs (vehicle acquisition costs including taxes, insurance, garaging) for cars. Similar kinds of parameters that model the volume of travel on other modes are needed. They should include costs, geography, and change in infrastructure (for example, development of high-speed rail between cities, bus-rapid transit and metro systems within cities). Similarly analysis for freight is needed for longer-run modelling in both developed countries and especially in developing countries with low levels of vehicle fuel use.

The energy services approach recognises fuel economy (distance/energy) or fuel intensity (energy/distance) as a key concept. We recognise that this energy-services approach treats all cars and SUV/light trucks used by households as private vehicles alike. This oversimplifies a complex evolution by which power, weight, and other attributes of new cars have grown almost steadily over three decades (Schipper and Hedges, 2010). Put another way, the ratio of new vehicle test fuel intensity to either weight or power has grown by almost a factor of two from 1980 to 2008, yet test fuel intensity of new 2008 vehicles is lower than it was in 1980. Even more important, the ratio of power to weight, which is virtually the acceleration of a vehicle, has also grown markedly. Since weight is related to interior volume, this means that new vehicles have become both larger and faster, absorbing most of the technological improvements to new vehicles that could have saved fuel. This is a kind of rebound effect not accounted for here but worthy of future study, because the fuel intensity of future vehicles will be determined by whether or not these attributes continue to grow and eat away efficiency gains. Indeed, in 2008/9, new vehicles in the EU were on average slightly less massive and powerful than those sold in 2007. Interestingly, the aforementioned ratios that indicate technological efficiencies still fell, so that in 2009 both car attributes and efficiency moved in a direction of lower fuel intensity. Clearly understanding these trends is key to modelling future specific fuel intensity.

The foregoing also introduces another variable not treated explicitly here, the difference between the tested fuel intensity of new vehicles and what they obtain in real traffic. Schipper and Tax (1994) reviewed this “gap” across a number of countries. Smokers et al. (2006) puts the gap in Europe at nearly 20%, i.e., the sales-weighted test fuel intensities must be raised by some 20% to yield a more accurate estimate of what all the cars sold in a given year would obtain in real traffic. The US EPA now raises the sales-weighted new vehicle average intensity by about 25% to make up for this “gap”. In cold countries the gap is larger because weather affects the time it takes a conventional engine to warm up, while in Sweden, with a smaller share of car use in congested urban areas, the gap is smaller despite the cold climate (Schipper and Tax, 1994).

One problem plaguing research is the source of energy-use data for transport itself. On the one hand, nationwide, statistically valid monitored data for any mode of passenger transport are not

available other than in a few countries with surveys extending to all modes. Energy consumption by mode is often calculated from energy consumption divided by fuel intensity. With respect to these relations between fuel intensity and miles or kilometres driven, we know already from Schipper et al. (1993a) the problem of the vicious circle. Distance driven is calculated from energy and fuel intensity or vice versa. Thus, well known inaccuracies in either of these components is carried forward to the computation of the other.

Another important point overlooked by most elasticity estimates but noted in Basso and Oum (2007) and earlier by Schipper et al. (1993b) is that increasingly, demand for vehicle fuel must be modelled carefully fuel by fuel and mode by mode. The correspondence between gasoline consumption and car use has changed over time in Europe, both because less and less gasoline has been used for all trucks and more and more cars (about 35% of the stock in the EU in 2008) run on diesel or LPG. These shifts meant that between 1973 and 1990, the rate of change of aggregate gasoline demand in European countries was only half as large as the rate of change (increase) in fuel demand for cars (see Fig. 4). In France, for example, more than half of the energy consumed by cars now is as diesel fuel, because diesel cars are driven so much farther than gasoline cars that their (small) advantage of lower fuel use/km is more than offset by the nearly 35% greater distances/car each is driven. Modelling gasoline demand in France would, thus, give an even more misleading picture of the demand for fuel for car travel than was the case when Schipper et al. (1993a) first quantified this “gap” in the early 1990s. Therefore, if the full car park is to be considered, fuel consumption of diesel and other fuelled-vehicles must be considered.

This also changes the average price paid for fuel because diesel and LPG have been priced historically much lower than diesel (Johansson and Schipper, 1997; Schipper and Fulton, 2009; Ajanovic and Haas, this issue). Statistical analysis of gasoline demand alone would thus overestimate the price in later years (as more lower-cost diesel and LPG was used) and underestimate the real growth in demand for car fuel. Worse, motorcycles account for a large part of gasoline demand in some regions (South and Southeast Asia).

If in the future, vehicles are powered increasingly by electricity or natural gas, then the question of oil demand as “fuel” has to be modified considerably, as noted in IEA (2009). Thus, both the energy sources and vehicles may diverge from a simple approach described by “cars” and “gasoline” consumption.

Another complication arises because the demand for diesel fuel itself is increasingly split between cars and trucks in Europe, trucks and buses in Latin America and cars, trucks, and buses in Asia. Thus, the demand for “road fuels” does not correspond to the demand for any one transportation service, while the demand for any one transportation service is either satisfied by several fuels (car travel) or by a fuel that is shared by all three road modes (diesel fuel). While most developed countries now publish consumption of fuel by type and by vehicle (i.e., cars, two wheelers, buses, trucks), no developing countries keep regular accounts of these modes of consumption nor account of the transportation services (in vehicle-, passenger- or tonne-kilometres) for road transport. Regression analysis may be able to project overall oil demand in this sector using fuel prices and incomes, but that tells us very little about how transport itself evolves with development.

Other important uses of oil today in transport are international and domestic air travel, domestic waterborne freight (significant in large countries) and fuel for internationally waterborne freight (bunkers). In large countries (India, China, Russia, Canada, Australia, and the U.S.) fuel oil for rail freight can also be important. While we did not focus on these fuels, it is important

to note that air travel (and air freight) continue to grow because of the advantage of speed (Schaefer et al., 2010).

Electrified high-speed rail has made some inroads in air travel at great energy and CO₂ savings, but generally in the range 50–600 km. While air travel is energy intensive in this range, such travel represents only a small share of air (and car) travel, hence the overall impact of high speed rail on fuel use in cars and air travel will be small except in the corridors where high speed rail is justified (Kosinski et al., 2011). If the “high” projections of electric light duty vehicles from IEA (2009) are realized, then this mode and not high speed (or even conventional) rail and electrified urban transport will dominate future demand for electricity in transport.

Finally, attempts to restrain CO₂ emissions by changing transport policies may have profound impacts on the demand for transport services and mode share, and thereby affect transport fuel demand beyond what traditional price/income models show. This is because externalities related to transport (safety, congestion, air pollution and others noted in Table 4) are generally more costly to society relative to vehicle-km than those for CO₂ or even those imposed for energy security (Parry et al., 2007).

So, looking at the manifold of impact parameters beyond rather than just looking at transport fuels should provide a more in-depth understanding of which parameters drive demand for transport and corresponding energy consumption. Developing a modelling approach where future demand is driven by transportation factors related to passenger travel and freight (i.e., the energy services discussed herein) and modified by vehicle characteristics, vehicle technology, fuel choice and driving conditions may provide more clues to the future than simply modelling oil demand alone, if for no other reason than the increasing prospects for vehicles that do not use oil.

We summarise our above ‘discussion of potential modelling avenues by challenging researchers and policy makers: (i) to consider transport fuel use in the broader context of transport and land use policy; (ii) to extend modelling of transport (energy) demand towards other sectors than road transport; (iii) to focus on modelling of switching between powertrains (e.g., towards electric and fuel cell vehicles) and between modes; (iv) to promote resources for more reliable data on various components related to transport demand; (v) to include in addition to prices and income other relevant parameters taking into account, e.g., cultural and life-style issues and possible saturation constraints; and (vii) to get a better understanding of the role of transport and transport energy use in the economic development of nations.

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